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EQUATION OF STATE OF SOLIDS. II. ALUMINUM AND TEFLON. (U)

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IDENTIFIERS: ALUMINUM ALLOY 2024, GAS GUNS, HUGONIOTS, TEFLON (U)

THE PRESSURE-VOLUME-ENERGY (P-V-E) EQUATION OF STATE OF ALUMINUM AND TEFLON HAS BEEN INVESTIGATED. THE P-V-E EQUATION OF STATE OF A MATERIAL IS NEEDED TO SOLVE NONREACTIVE FLOW PROBLEMS USING COMPUTER CODES SUCH AS PUFF. EXPLOSIVELY INDUCED SHOCK WAVES HAVE BEEN USED TO GENERATE HUGONIOT CURVES FOR SOLID AND POROUS SPECIMENS OF ALUMINUM AND TEFLON. FOR ALUMINUM IT IS FOUND THAT THE FOLLOWING P-V-E EQUATION OF STATE CAN REPRODUCE THE EXPERIMENTAL DATA QUITE NICELY: P = BE + G(V) B IS A CONSTANT AND G IS AN ARBITRARY FUNCTION OF V. THIS CORRESPONDS TO GAMMA/V = CONSTANT, WHERE GAMMA IS GRUNEISEN'S RATIO. BECAUSE OF THE SPREAD OF THE TEFLON DATA IN THE P-V PLANE, IT WAS NOT POSSIBLE TO OBTAIN A P-V-E FIT. HOWEVER, THE DATA IMPLY THAT GRUNEISEN'S RATIO VARIES FROM ABOUT 0.7 TO 1.4 AT HIGH PRESSURES. GAS GUN EXPERIMENTS USING MANGANIN WIRE PRESSURE RECORDINGS WERE PERFORMED. SOUND SPEEDS DEDUCED ROM THESE RECORDS IMPLY THAT TEFLON BECOMES ANOMALOUSLY STIFF UNDER SHOCK. (AUTHOR) (U)

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EQUATION OF STATE OF SOLIDS
II
ALUMINUM AND TEFLON

G. D. Anderson
A. L. Fahrenbruch

Stanford Research Institute
Poulter Laboratories
Menlo Park, California 94025
Contract AF 29(601)-7214

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September 1967

AIR FORCE WEAPONS LABORATORY
Research and Technology Division
Air Force Systems Command
Kirtland Air Force Base
New Mexico

AFWL-TR-67-43

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A. L. Fahrenbruch

Stanford Research Institute
Poulter Laboratories
Menlo Park, California 94025
[redacted] AF 29(601)-7214

SRI-FGU-

TECHNICAL REPORT [redacted]

FOREWORD

This report was prepared by the Poulter Laboratories, Stanford Research Institute, Menlo Park, California, under Contract AF 29(601)-7214. The research was performed under Program Element 6.16.46.01D, Project 5710, Subtask 15.018, and was funded by the Defense Atomic Support Agency (DASA).

Inclusive dates of research were 6 May 1966 to 6 May 1967. The report was submitted 11 July 1967 by the Air Force Weapons Laboratory Project Officer, Captain Raymond J. Lawrence, Jr. (WLRP).

The project supervisor was Dr. G. P. Anderson and the project leader was Mr. A. L. Fahrenbruch. The authors wish to thank Drs. D. G. Doran and M. Cowperthwaite for their contributions through discussions on equations of state, and Miss B. Y. Loo for shot analysis and computations.

Contractor's report number is SRI Project FGU-6047.

This technical report has been reviewed and is approved.

for John T. Viola
RAYMOND J. LAWRENCE, JR.
Captain, USAF
Project Officer

Harry F. Rizzo
HARRY F. RIZZO
Major, USAF
Chief, Physics Branch

Claude K. Stambaugh
CLAUDE K. STAMBAUGH
Colonel, USAF
Chief, Research Division

ABSTRACT

(Distribution Limitation Statement No. 2)

The pressure-volume-energy (P-V-E) equation of state of aluminum and Teflon has been investigated. The P-V-E equation of state of a material is needed to solve nonreactive flow problems using computer codes such as PUFF. Explosively induced shock waves have been used to generate Hugoniot curves for solid and porous specimens of aluminum and Teflon. For aluminum it is found that the following P-V-E equation of state can reproduce the experimental data quite nicely:

$$P = bE + g(V)$$

b is a constant and g is an arbitrary function of V. This corresponds to Γ/V = constant, where Γ is Gruneisen's ratio. Because of the spread of the Teflon data in the P-V plane, it was not possible to obtain a P-V-E fit. However, the data imply that Gruneisen's ratio varies from about 0.7 to 1.4 at high pressures. Gas gun experiments using manganin wire pressure recordings were performed. Sound speeds deduced from these records imply that Teflon becomes anomalously stiff under shock.

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ILLUSTRATIONS

TABLES

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SECTION I

INTRODUCTION

In order to predict the shock wave propagation and flow resulting from a stress suddenly applied on the surface of a material, it is necessary to know the pressure-volume-energy (P-V-E) equation of state of the material under consideration. Equations of state for use in the PUFF code are of particular interest. It has been the practice to use a Mie-Gruneisen form of equation of state to describe solids. This equation of state is derived by using an assembly of harmonic oscillators as a model to describe solids. It is assumed that the logarithmic change of frequency with volume is the same for all frequencies and this leads to Gruneisen's ratio, which depends upon specific volume (Ref. 1). The purpose of this work has been to study the range of pressures and volumes for which it is valid to apply the Mie-Gruneisen equation of state to solids and to determine Gruneisen's ratio.

The work reported here is a continuation of work described in Reference 2. Specifically, the work has been aimed at obtaining equation of state data on aluminum and Teflon,* using shock wave compression of porous specimens. The emphasis in the earlier work was on aluminum. The present work has concentrated on generating more Teflon data although some porous aluminum data were obtained to supplement the earlier data. The new aluminum data slightly shift one of the Hugoniots that was obtained earlier.

The new high-pressure Teflon data are in good agreement with those obtained earlier. In addition to the high pressure data from explosive tests, some lower pressure data from gas gun experiments are presented. The low pressure data include manganin wire gage measurements of stress profiles at different depths in the target material.

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SECTION II

EXPERIMENTAL TECHNIQUE

1. Explosive Technique

The explosive technique used to generate the high pressure aluminum and Teflon data is described in detail in Ref. 2. The technique consists of explosively accelerating a flat metal plate that impacts a 2024 aluminum driver plate upon which the samples are mounted. Measurements are made of the free-surface velocity of the aluminum driver plate and of the shock velocity through the sample. These data, combined with the loading and unloading curves in the pressure-particle velocity plane for the 2024 aluminum, are sufficient to compute Hugoniot points for the sample material using the impedance match technique (Ref. 3). In this technique, it is assumed that a steady state plane shock wave exists in the sample material and in the 2024 aluminum driver plate. Experiments on samples of varying thickness indicate that this assumption is valid for homogeneous samples if care is taken to prevent side and rear rarefactions from overtaking and interacting with the shock. The assumption is more questionable in very heterogeneous media such as granular or porous materials. The data have been treated here assuming steady state.

All measurements of shock and free-surface velocity were made optically by using a rotating mirror streak camera. The present data were obtained on 70-mm film using a Beckman and Whitley Model 770 camera. This camera has a maximum writing speed of 10 mm/μsec as compared to a maximum of 3.84 mm/μsec for the 35-mm-camera used in the earlier work.

2. Gas Gun Technique

Low-pressure experiments on Teflon were performed using a 2-1/2-inch-diameter gas gun projectile to generate shock waves. The projectile head is made either of Teflon to match the target or of 2024 aluminum. A schematic diagram of the shot assembly mounted at the muzzle of the gun is shown in Fig. 1. The projectile is accelerated down the evacuated

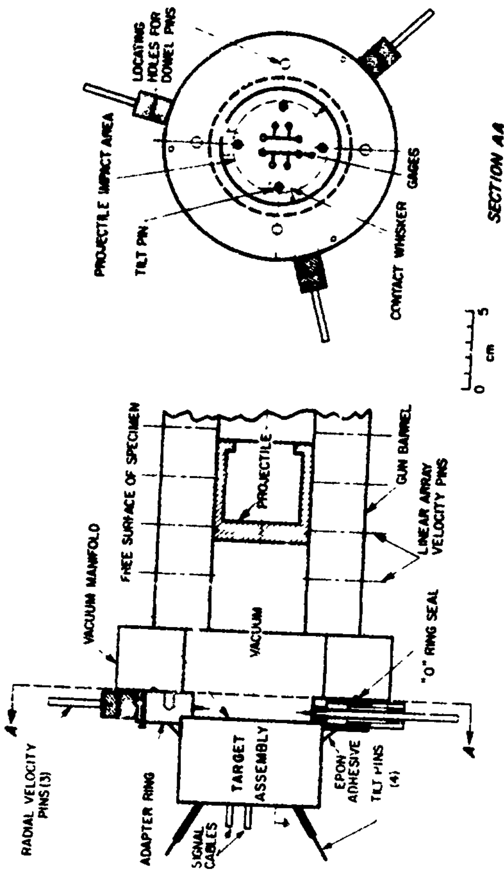

FIG 1 CROSS-SECTION VIEW OF TARGET ASSEM.LY MOUNTED ON MUZZLE OF GAS GUN

gun barrel b\ helium from a high pressure reservoir. The projectile velocity is measured near the muzzle of the barrel by a linear array of four pins spaced at intervals of one-tenth foot. The arrival of the projectile is also detected by three radial velocity pins placed in front of the specimen impact surface. Four tilt pins, passing through the target in a square array at 90° intervals, record the actual impact and provide a measure of the nonsimultaneity of impact (tilt). Tilt is minimized by carefully preparing flat target and projectile faces and aligning the target face perpendicular to the axis of the gun barrel The target alig.ment technique has been described by Linde and Schmidt (Ref. 3).

Stress-time profiles in the target were recorded using manganin wire gages. Two gages were mounted in each target assembly as shown in Fig. 2. One gage wire is mounted on the impact surface and is covered by either a 0.001-inch layer of Mylar or a thin Teflon shim. The second gage wire is placed between two Teflon disks, which are bonded together with a thin layer of epoxy. In making a stress measurement, a constant current is passed from a triggered power supply through the piezoresistive element from terminal A to A′ (Fig. 2). The initial resistance and the change in resistance of the element due to passage of the wave are measured by recording the voltage B-B′ as a function of time. The ratio of the change in resistance to the initial resistance (this is equivalent to the ratio of the change in voltage to the initial voltage for a constant current) is proportional to the stress A detailed description of the operation of the gage is given in Ref 4

3. Specimen Materials

The porous aluminum specimens were cold p-.ssed to the desired density f-o.. Reynolds No. 40 atomized aluminum powder, which is greater than 99 percent pure aluminum. For specimens of porosity ' m = 1.4 and m = 1.7,*

*Porosity m is defined by $m = \rho_o/\rho_{app}$ where ρ_o is the crystal density at standard conditions and ρ_{app} is the apparent density under the same conditions

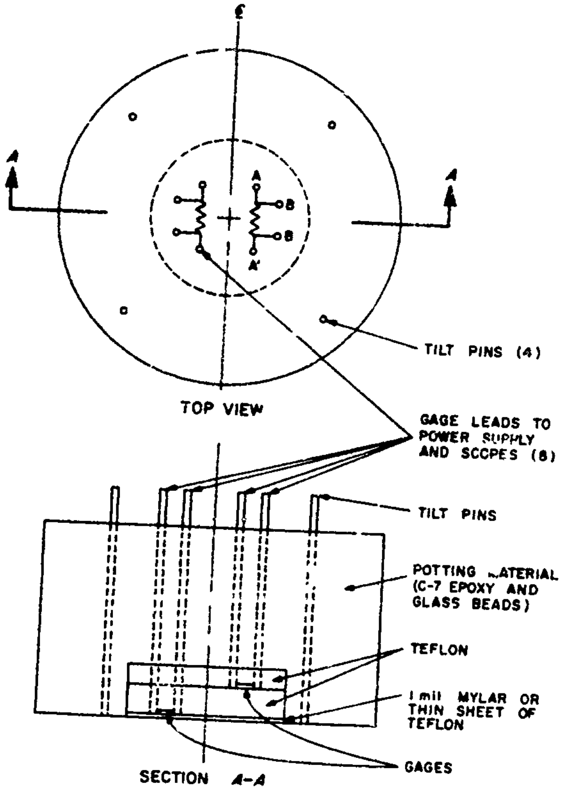

FIG 2 TARGET ASSEMBLY

the powder was screened and only those particles less than 200 μ were used. The specimens were quite strong mechanically, machinable, and easily handled. Specimens of porosity m = 2.0 were made of powder between 200 μ and 300 μ. These were somewhat more fragile. The raw material and specimen preparation were reported in Ref. 2. Specimens were nominally 1/8 inch thick by 1 inch in diameter.

The solid and porous Teflon were obtained from the Avco Corporation, where low pressure work on aluminum and Teflon was also performed. The preparation of these samples is described in Ref. 5.

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SECTION III

EXPERIMENTAL RESULTS AND ANALYSIS

1. Aluminum

The Hugoniot data for solid and porous aluminum are presented in Table I. All of the data reported in Ref. 2 are included so that Table I is a complete summary. The data for porous aluminum are plotted in the shock velocity-particle velocity plane in Fig. 3. The straight lines in the figure are drawn as guides and do not represent fits to the data. The Hugoniots in the pressure-volume plane are presented in Fig. 4 (the labels $t = 3/16$ in. and $t = 3/8$ in. refer to the sample thickness). The Hugoniot for solid aluminum was taken from the work of Al'tshuler et al. (Ref. 6). They quote a value of 2.71 g/cm^3 for the initial density of aluminum. To make their Hugoniot comparable to the data reported here on aluminum of initial density 2.70 g/cm^3, each of their volumes at a given pressure was changed by a factor of 2.71/2.70. This maintains the shape of the curve but translates it slightly to the right, i.e., toward larger specific volumes. The solid Hugoniot curve was then fitted by

$$P_H = 16889.5 - 134337.5V + 363023V^2 - 333405V^3 \quad (1)$$

where V is specific volume in cm^3/g and P_H is Hugoniot pressure in kilobars. To fit the porous aluminum pressure-volume (P-V) data, smooth curves were drawn through the points. From these curves and the solid aluminum Hugoniot, the internal energy as a function of pressure at a given volume was computed by using the Hugoniot energy relation

$$E_H = E_o + (1/2)P_H(mV_o - V) \quad (2)$$

where m is the porosity. The values of the initial internal energy E_o and the initial specific volume V_o were taken as 1.66×10^{5} ergs/gm and

Table 1

SOLID AND POROUS ALUMINUM HUGONIOT DATA

Shot No.	Initial Volume (cm^3/gm)	Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kbar)	Final Volume (cm^3/gm)	Internal Energy Change (10^9 erg/gm)
m = 1.0						
11,477	0.370	7.31	1.45	286	0.297	10.65
11,570	0.370	7.75	1.80	377	0.284	16.21
11,563	0.370	8.77	2.46	583	0.266	30.31
11,460	0.370	9.06	2.58	633	0.265	33.23
11,562	0.370	9.13	2.71	667	0.260	36.56
m = 1.4						
11,477	0.519	5.08	1.88	184	0.328	17.57
12,778	0.518	5.17	1.89	189	0.328	17.95
12,791	0.518	5.36	1.84	191	0.339	17.09
12,283	0.519	6.43	2.45	304	0.321	30.09
12,535	0.518	6.83	2.70	357	0.313	36.59
12,908	0.518	6.90	2.77	368	0.310	38.27
10,591	0.520	7.19	3.03	418	0.299	46.18
10,562	0.521	7.79	3.42	511	0.293	58.25
12,536	0.521	7.97	3.45	528	0.296	59.40
m = 1.7						
11,155	0.629	5.43	2.43	210	0.347	29.61
11,286	0.631	5.82	2.67	246	0.341	35.67
11,062	0.629	5.93	2.69	254	0.344	36.19
10,878-1	0.630	6.58	3.05	319	0.338	46.57
10,878-2	0.629	6.50	3.06	316	0.333	46.76
10,926	0.631	6.83	3.20	347	0.335	51.35
11,330	0.631	6.90	3.25	355	0.334	52.72
10,591	0.633	6.91	3.26	356	0.334	53.22
10,894	0.637	7.29	3.44	397	0.333	58.95
11,305	0.631	7.49	3.58	426	0.330	64.11
10,592	0.635	7.55	3.66	436	0.327	67.14
m = 2.0						
11,155	0.741	5.09	2.58	177	0.365	33.19
11,286	0.741	5.57	2.82	214	0.364	33.85
11,062	0.741	5.64	2.85	218	0.367	40.76
10,926	0.741	5.72	3.37	305	0.369	56.73
11,330	0.740	6.79	3.41	313	0.369	58.06
10,894	0.741	7.16	3.60	348	0.368	64.90
11,379	0.744	7.29	3.85	377	0.351	74.08
11,305	0.741	7.32	3.78	373	0.360	71.05

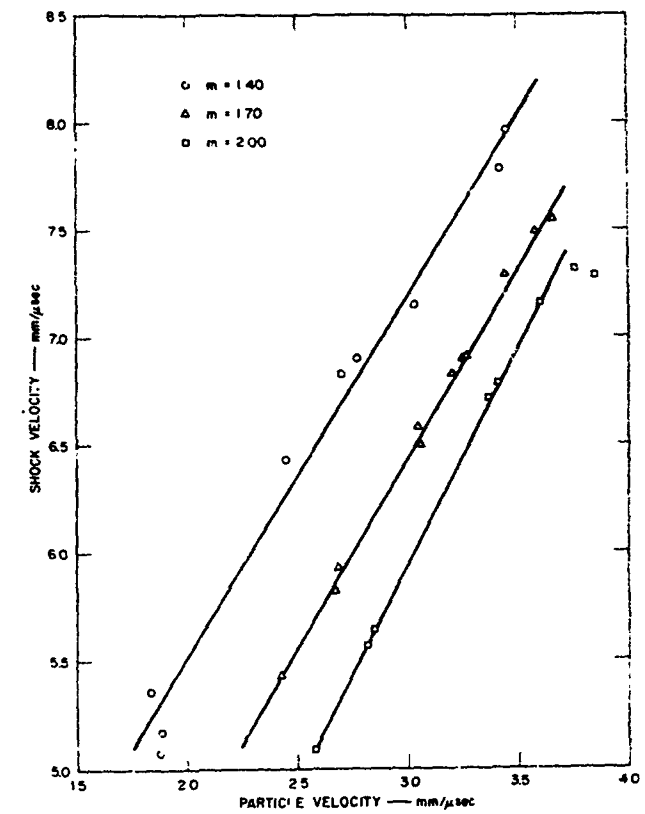


FIG 3 SHOCK VELOCITY vs PARTICLE VELOCITY FOR POROUS ALUMINUM

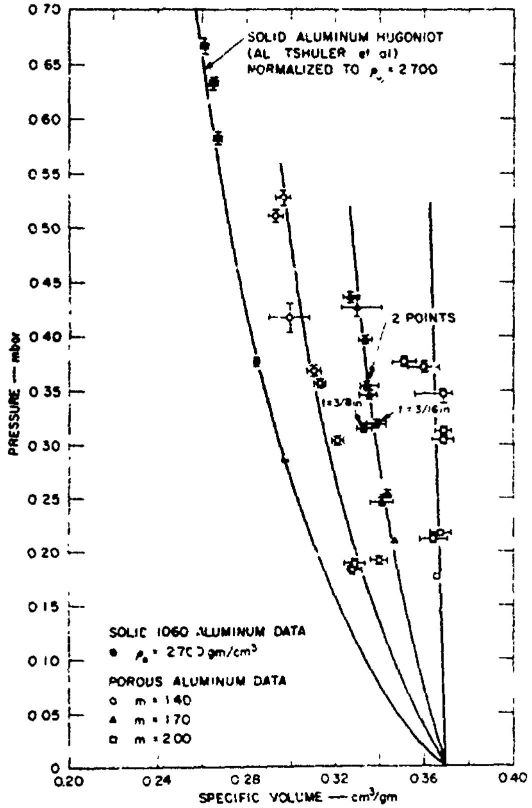


FIG. 4 HUGONIOTS FOR ALUMINUM

0.370 cm^3/gm, respectively. As can be seen from Fig. 4, a maximum of three energy-pressure points can be computed at a given volume in the volume range where the Hugoniots for $m = 1$, 1.4, and 1.7 overlap. Several points can be computed near $V = V_o$ from the Hugoniot for $m = 2.0$. Plots of the energy vs. pressure at constant volume are straight lines, indicating that $(\partial P/\partial E)_V$ is a function only of volume; furthermore, the fact that all slopes are nearly the same indicates that $(\partial P/\partial E)_V$ is nearly constant. The energy-pressure-volume equation of state data can then be fitted by a form

$$P = bE - g(V) \tag{3}$$

where $b = (\partial P/\partial E)_V$, a constant, and g is an arbitrary function of V. From the pressure-energy plots, an average value of $b = 5.15$ gm/cm^3 was obtained. The function $g(V)$ was computed by substituting Eqs. (1) and (2) into Eq. (3) for P and E, respectively. A fit for $g(V)$ was then found to be given by

$$g(V) = 8721.138 - 66012.96V + 171668.7V^2 - 154117.1V^3 \tag{4}$$

where V is in cm^3/gm and $g(V)$ is in kilobars. The Hugoniot curves drawn in Fig. 4 were generated from the equation of state given by Eq. (3) with $b = 5.15$ gm/cm^3 and $g(V)$ given by Eq. (4). This form of the equation of state is a Mie-Gruneisen equation with Γ/V a constant, where Γ is Gruneisen's ratio.

The Hugoniot curves in the pressure-volume plane for the various porosities are given by

$$P_H(V) = \frac{bE_o + g(V)}{1 - \frac{b}{2}(mV_o - V)} \tag{5}$$

The minimum volume to which a porous material can be compressed is given by

$$V_{min} = mV_o - \frac{2}{b} \tag{6}$$

Setting $V_{min} = V_o$ in Eq (6) shows that the Hugoniot of aluminum of porosity $m = 2.05$ would be a vertical line passing through $V_o = 0.370\ cm^3/gm$. The Hugoniot curves for $m = 1.4$, 1.7, and 2.0 drawn in Fig. 4 were generated by Eq. (5). With the exception of the highest pressure point for $m = 2.0$, Eq. (5) seems to fit the data quite well.

A fit to the data using μ ($\mu = \rho/\rho_o - 1$) as a variable is discussed in the Appendix.

2. <u>Teflon</u>

The Hugoniot data for Teflon obtained from the explosive tests are presented in Table II. Plots of the data in the shock velocity-particle velocity plane and the pressure-volume plane are presented in Figs. 5 and 6, respectively. The four lowest pressure points for solid Teflon on Figs. 5 and 6 are from gas gun shots (Table III). These four points and the lowest pressure explosive data point for solid Teflon exhibit a slightly steeper slope in the shock velocity-particle velocity plane than do the remaining points. This change in slope produces the cusp shown by the dashed line in the pressure-volume diagram. However, the lowest pressure explosive data point is questionable because the optical record was poor, and so the cusp is shown as a dashed line to indicate that not too much significance should be attached to it.

Since the Hugoniot data for the two porosities of Teflon ($m = 1.42$ and $m = 2.77$) do not overlap in volumes, only two energy-pressure points can be computed for any one volume. The uncertainties in the volume at a given pressure on the Hugoniots of porous Teflon are also quite large. Values of the average Gruneisen ratio as calculated from the offsets of the Hugoniots in Fig. 6 run from 1.2 to 1.4 when calculated between the solid and $m = 2.77$ Hugoniots. Quite large internal energy increases occur along the Hugoniot of porosity $m = 2.77$, and it is quite possible that some decomposition takes place.

The gage records for gas gun shots (Table III) generally indicate a lower pressure than that computed by the impedance match technique using the projectile velocity and the shock velocity in the sample.

Table II

TEFLON HUGONIOT DATA FROM EXPLOSIVE TESTS

Shot No.	Initial Density (gm/cm^3)	Shock Velocity (mm/μsec)	Particle Velocity (mm/μsec)	Pressure (kbar)	Final Volume (cm^3/gm)	Energy Increase (10^9 erg/gm)
			m = 1.00			
12,495	2.157	3.529	1.075	82.0	0.3224	5.78
12,778	2.168	5.120	1.833	203.0	0.2959	16.78
11,570	2.169	5.589	2.215	269.0	0.2782	24.58
12,284	2.175	5.628	2.205	269.5	0.2760	24.75
12,283	2.170	5.994	2.415	314.0	0.2752	29.56
12,535	2.169	6.360	2.665	368.0	0.2678	35.54
11,563	2.163	6.830	2.945	435.0	0.2629	43.37
11,460	2.172	7.105	3.080	476.0	0.2608	47.50
11,562	2.163	7.262	3.200	504.0	0.2582	51.35
12,536	2.169	7.543	3.375	552.5	0.2547	57.26
			m = 1.42			
12,495	1.533	2.639	1.255	50.5	0.3442	7.77
12,778	1.524	4.354	2.120	140.5	0.3366	22.45
11,570	1.517	4.909	2.555	190.3	0.3160	32.64
12,284	1.525	4.952	2.535	191.5	0.3201	32.13
12,535	1.516	5.774	3.065	268.0	0.3094	46.92
11,563	1.524	6.207	3.373	319.0	0.2995	56.87
11,562	1.515	6.683	3.660	371.0	0.2981	66.97
12,536	1.516	6.992	3.855	408.5	0.2959	74.28
			m = 2.77			
12,495	0.7967	2.048	1.420	23.0	0.3849	10.00
12,778	0.7606	3.741	2.493	71.0	0.4385	31.10
11,570	0.7828	4.374	2.985	103.0	0.4057	44.87
12,284	0.7782	4.340	2.980	100.8	0.4027	44.46
12,535	0.7870	5.129	3.600	146.0	0.3788	65.13
11,563	0.7782	5.646	3.985	175.5	0.3780	79.58
11,562	0.7828	6.086	4.335	207.0	0.3676	84.12
12,536	0.7869	6.419	4.565	231.0	0.3670	104.4

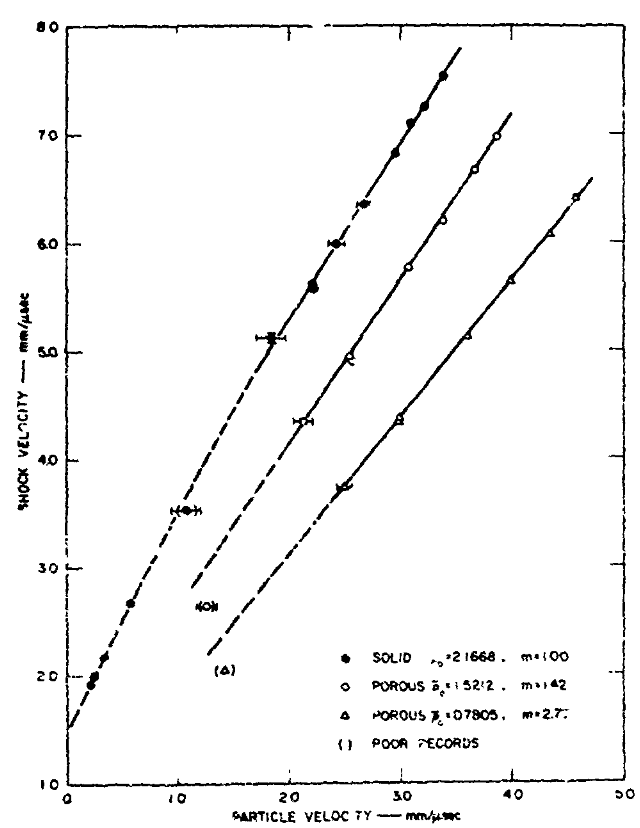


FIG. 5 SHOCK VELOCITY vs PARTICLE VELOCITY FOR TEFLON

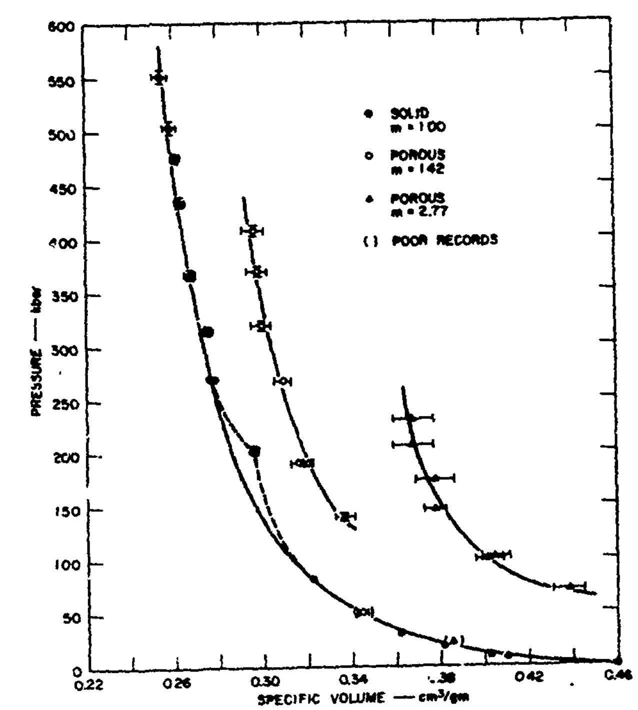


FIG. 6 TEFLON HUGONIOT DATA

Table III

TEFLON HUGONIOT DATA FROM GUN SHOTS

Shot No.	Projectile		Shock Velocity (mm/μsec)	Pressure (kbar)			Particle Velocity (mm/μsec)	Volume[b] (cm^3/gm)
	Velocity (mm/μsec)	Material		Impedance Match	Gage 1	Gage 2[a]		
12,872	0.417	Teflon	1.92	8.7	8.6[c]	8.1	0.208	0.410
12,897	0.311	Aluminum	2.00	10.8	8.8[d]	9.1	0 247[e]	0.403
12,857	0.741	Teflon	2.17	17.6	15.9[c]	15.6	0.370	0.382
12,873	0.781	Aluminum	2.67	33.5	34.2[f]	29.8	0.578[e]	0.361

[a] Gage 2 is approximately 6.4 mm behind Gage 1 except Shot 12,897, in which it is 4.76 mm from Gage 1.

[b] From shock and particle velocities.

[c] Gage on impact surface covered by 1 mil Mylar.

[d] Gage 1.5 mm from impact surface.

[e] From impedance match using measured shock velocity.

[f] Gage 1.7 mm from impact surface.

In Shot 12,872 the projectile head was a 3.03 mm disk of Teflon backed by aluminum. The Teflon target had one gage on the impact surface covered by a 0.001-inch layer of Mylar and a second gage 6.44 mm from the impact surface. Due to a timing error, the fast sweep oscilloscope record from the first gage was lost. A plot of the record from the second gage is shown in Fig. 7. This gage record indicates a double wave structure with a 2 to 3 kbar wave leading the 8 kbar peak wave by about 0 15 μsec. This structure was also observed on the long duration records of the second gage but not on the long duration record of the first gage, and thus exhibits the properties of a propagating double wave. Upon impact a shock is induced in the Teflon projectile head, which propagates back and reflects from the aluminum projectile as a second shock into the Teflon. The arrival of this second shock at the deeper gage produces the second pressure rise seen at about 2.25 μsec after arrival of the first wave. The final stress behind this wave is 12.3 kbar and a distance-time construction of the wave and particle paths indicates that the velocity of the reflected shock is about 3 mm/μsec with respect to the material.

For Shot 12,897 the projectile head was of 2024 aluminum. The peak pressures recorded by the two gages were somewhat higher than in Shot 12,872. The wave profiles, shown in Fig. 8, do not exhibit the "precursor" structure that was seen in the preceding shot (12,872). Both gage records show a very rapid pressure rise to 7 or 8 kbar and then a more gradually rounded rise to the peak stress. Similar behavior has been observed in polyethylene (Ref. 7). The decrease in pressure late in the gage record is due to the arrival of the rarefaction originating at the rear surface of the projectile. The time of arrival of this rarefaction indicates a sound speed of 2.82 mm/μsec at about 9 kbar in Teflon.

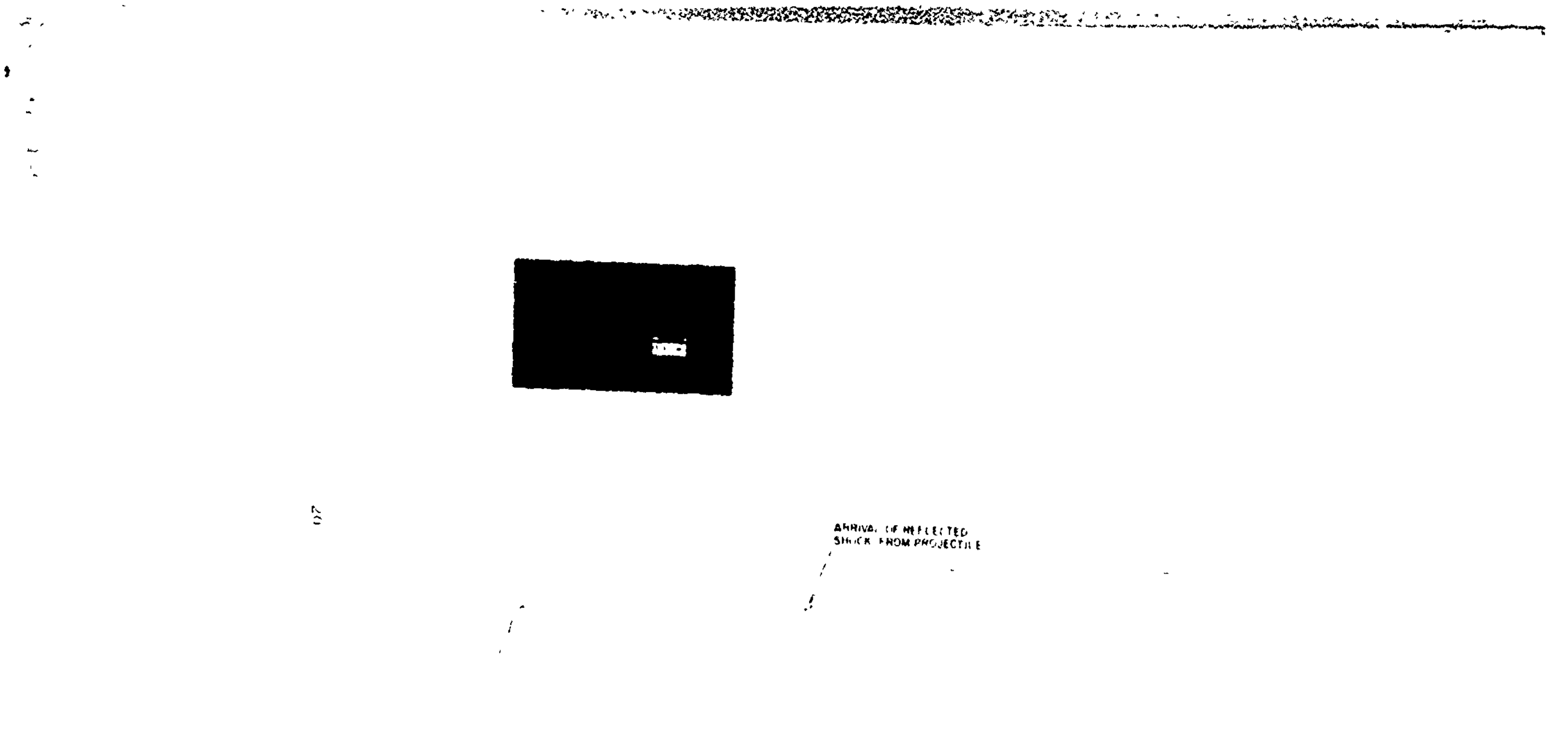
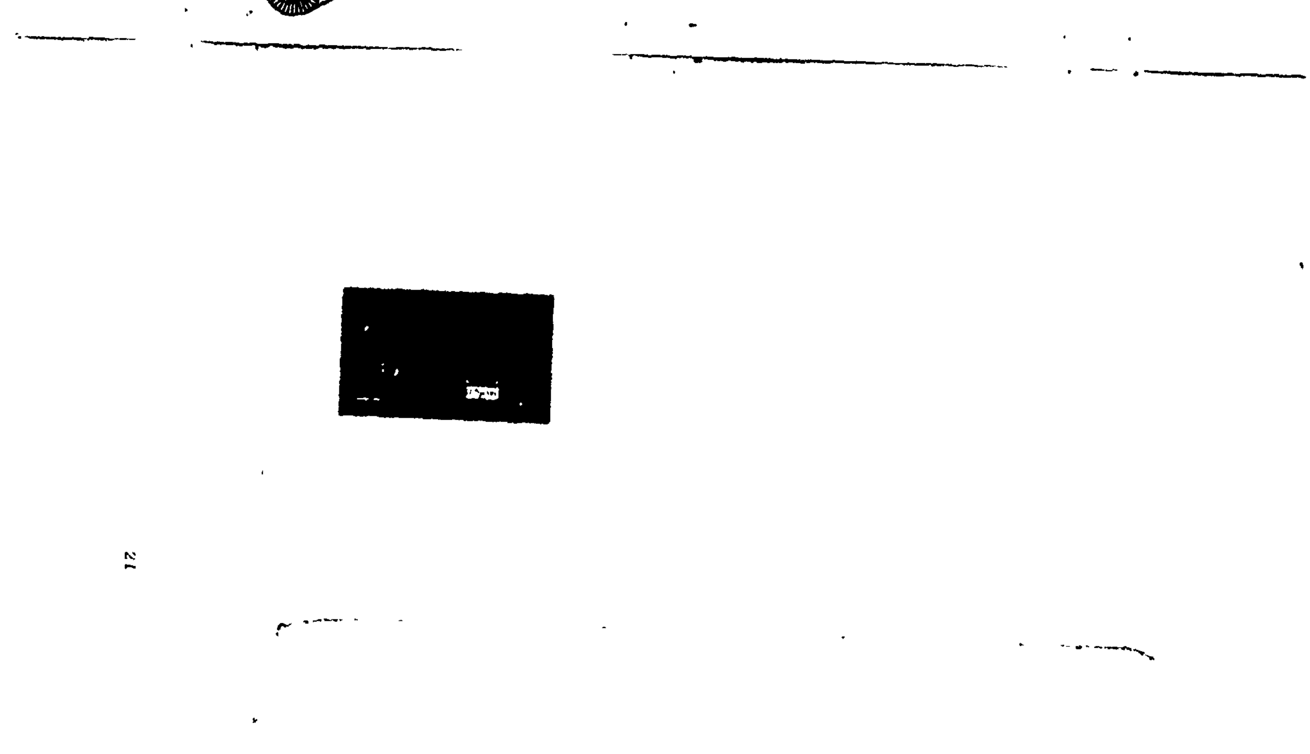
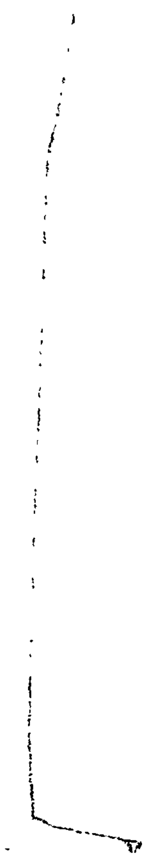


FIG 7 GAGE RECORD AND WAVE PROFILE FOR SHOT 12,872 SECOND GAGE



(a) FIRST GAGE

FIG. 8 GAGE RECORD AND WAVE PROFILE FOR SHOT 12,897

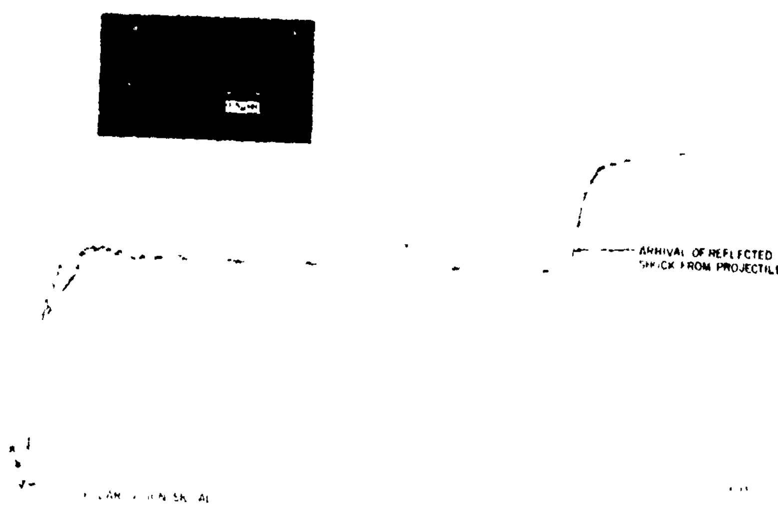


(b) SECOND GAGE

FIG. 8 (Concluded)

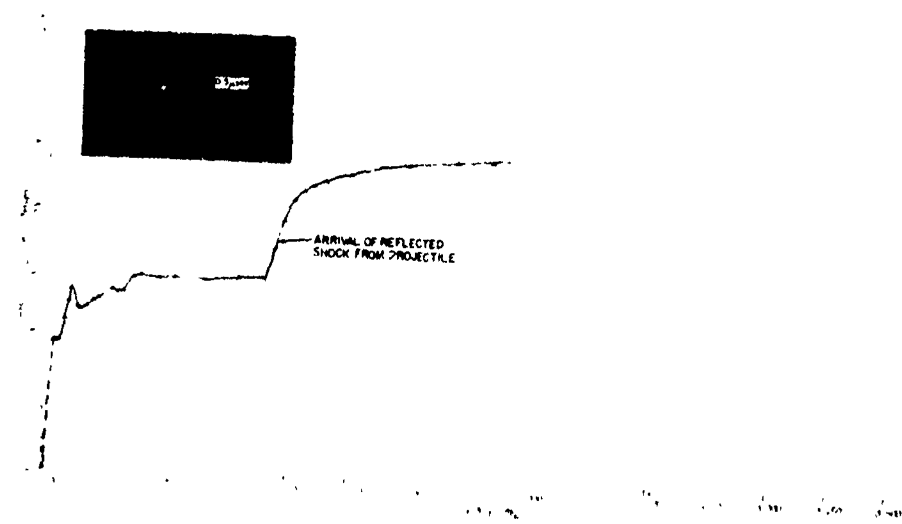
Shot 12,857 had a Teflon projectile head, which was 3.12 mm thick, backed by 2024 aluminum. The Teflon target had one gage on the surface covered by 0.001 inch Mylar and a second gage imbedded in Teflon 6.47 mm from the impact surface. The oscilloscope records and wave shapes from these records are plotted in Fig. 9. A polarization signal, possibly from shocking the Mylar cover, is observed before the pressure rise on the record from the first gage. Both gages record some oscillations before settling down to record the final peak pressure. However, the overshoot of pressure indicated by the first gage is not recorded by the second gage. Again the arrival of the reflected shock originating at the interface between Teflon and aluminum on the projectile is seen to arrive at the first gage about 2.25 μsec after the first wave and at the second gage at about 0.8 μsec after the arrival of the first wave. Recall that the time bases on the gage records begin with the arrival of the first wave at the gage position.

In the highest pressure gun shot, 12,873, an aluminum projectile struck the Teflon target. The oscilloscope records and plots of the wave shapes are presented in Fig. 10. The records indicate a rounding of the wave front and a decrease in peak pressure amplitude as the wave propagates from gage 1 to gage 2. The small oscillation that appears on the wave front was observed in varying degrees on all but the lowest pressure shot. Both gage records show a decrease in pressure resulting from the arrival of the rarefaction originating from the back surface of the projectile. From the time of arrival of this rarefaction a sound speed of 3.77 mm/μsec at 34 kbar was computed. Note in the record from gage 2 the arrival of a shock reflected from the potting compound behind the Teflon target.



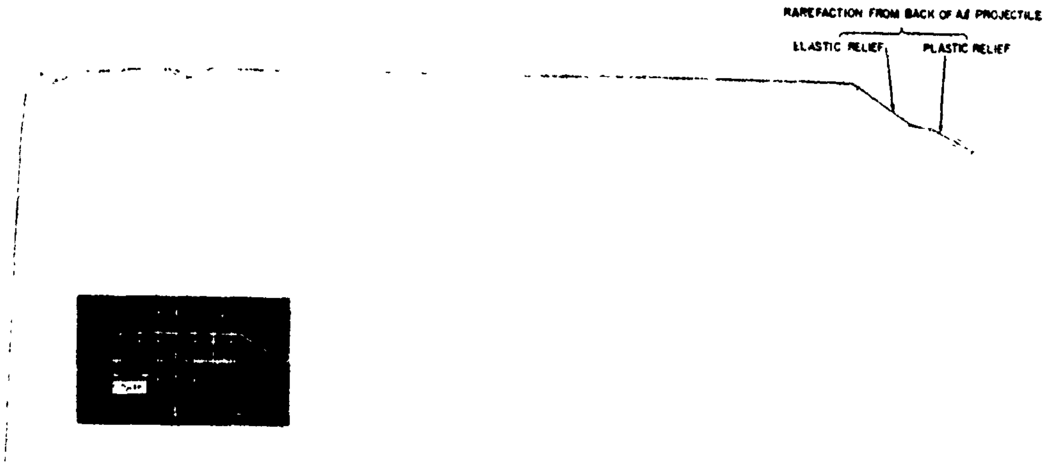
(a) FIRST GAGE

FIG. 9 GAGE RECORD AND WAVE PROFILE FOR SHOT 12,857



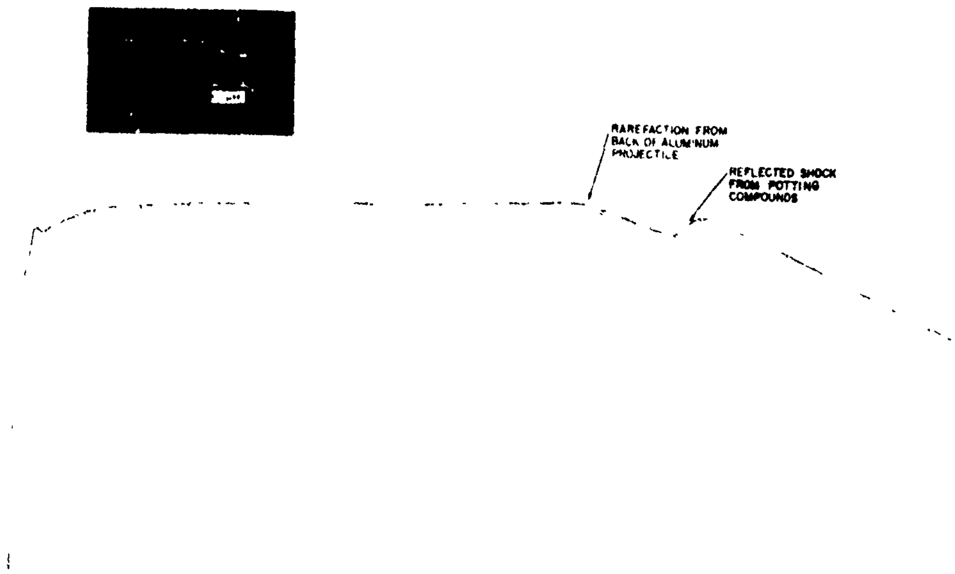
(b) SECOND GAGE

FIG. 9 (Concluded)



(a) FIRST GAGE

FIG 10 GAGE RECORD AND WAVE PROFILE FOR SHOT 12,873



(b) SECOND GAGE

FIG 10 (Concluded)

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SECTION IV

CONCLUSIONS AND SUMMARY

The pressure-volume-energy data for aluminum in the region of the P-V plane bounded by the Hugoniot of solid aluminum to 700 kbar and the vertical line through $V_o = 0.370\ cm^3/gm$ up to about 400 kbar are well represented by a simple Mie-Gruneisen equation of state of the form

$$P = bE + g(V) \qquad (3a)$$

where b is a constant equal to $5.15\ gm/cm^3$. The function $g(V)$ is a cubic in V given by

$$g(V) = 8721.138 - 66012.96V + 171668.7V^2 - 154117.1V^3 \qquad (4a)$$

This form of the Mie-Gruneisen equation in which the pressure is directly proportional to the internal energy at a given volume implies that Gruneisen's ratio $\Gamma[\Gamma = V(\partial P/\partial E)_V]$ is proportional to volume.

Owing to the steepness of the Hugoniot curves in the P-V plane it is extremely difficult to accurately determine an average Gruneisen's ratio from offsets in pressure and energy at a given volume. The shock wave data give the locus of points on the P-V-E surface but, because of the steepness of the surface compared with the precision of the experiments, it is very difficult to obtain accurate values for the derivatives of the surface. What has been done by introducing Eq. (3) has been to assume a form of P-V-E equation of state and force it to fit the data. There may be other analytical forms that fit the data equally well or perhaps even better. However, the simplicity of Eq. (3) in which pressure is proportional to energy would seem to make it desirable for computational work.

There is not enough overlap in volume of the Hugoniots of solid and porous Teflon to permit more than two energy-pressure points to be obtained at one volume. Values of Gruneisen's ratio computed *from the offsets* in pressure and energy along the Hugoniot curves vary by a factor of 2 (0.7 to 1.4). The zero pressure value estimated from static values of the bulk modulus, thermal expansion coefficient, and specific heat is about 0.313 (Ref. 2).

Sound speeds computed from the time of arrival at the gages of the rarefaction originating from the back surface of the aluminum projectiles on Shots 12,897 and 12,873 appear *anomalously high*. *An estimate* of the slope of the Hugoniot in the P-V plane can be obtained from the slope of the Teflon Hugoniot in the shock velocity-particle velocity plane (U-u plane). Since the U-u Hugoniot has less curvature than the P-V Hugoniot, the derivative dU/du can probably be more accurately determined from a plot of the data than can the derivative dP_H/dV. The two derivatives are related by

$$\frac{dP_H}{dV} = c_o^2 U^2 \left[\frac{u \frac{dU}{du} + U}{u \frac{dU}{du} - U} \right] \qquad (7)$$

The "Hugoniot sound speed" C_H *is then defined* by

$$C_H^2 = -V^2 \frac{dP_H}{dV} \qquad (8)$$

C_H should be *an upper limit for the sound speed of a hydrodynamic* material. From a graphical evaluation of the slope of the U-u curve for Teflon at the Hugoniot points for Shots 12,897 and 12,873, values of C_H have been estimated (Table IV).

Table IV
TEFLON SOUND SPEED DATA

Shot No	Pressure (kbar)	U (mm/μsec)	u (mm/μsec)	$\frac{dU}{du}$	C_H (mm/μsec)	C(meas) (mm/μsec)
12,897	10.8	2.03	0.208	2.22	2.37	2.82
12,873	33.5	2.67	0.579	2.00	3.31	3.77

In the two shots, the measured values of the sound speed, C(meas), appear to be 18 and 14 percent higher than C_H, the sound speed estimated *from the slope of the Hugoniot curve*. The implication of these admittedly meager data is that the material has undergone a change in properties, becoming stiffer than indicated by the Hugoniot. If one assumes that the material has rigidity and approximates the bulk modulus by ρC_H^2, the corresponding shear modulus is estimated to be ≈ 20 percent of the bulk modulus, and Poisson's ratio is ≈ 0.4. Although this is not an unreasonable number, its determination may be only a mathematical exercise. Also, there are two phase transitions in Teflon at about room temperature. One is at atmospheric pressure and the other at about 6.5 kbar. These phase transitions may be related to the anomalous behavior described above.

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APPENDIX

ANALYTICAL FITS TO THE EXPERIMENTAL DATA

The cubic fit to the Hugoniot of solid aluminum is given by Eq. (1). The coefficients are quite large numbers of oscillating sign, so that the pressure at a given volume is given by a sum of small differences of large numbers. This behavior indicates that a cubic fit to the data is probably not the best form. However, time does not permit further investigation of fits to the data to be included in this report.

For use in PUFF the variable $\mu = \rho/\rho_o - 1$ is used rather than the specific volume. A fit to the Hugoniot of solid aluminum in the variable μ is

$$P_H = 778.518\mu + 1165.95\mu^2 + 1416.69\mu^3 \qquad (9)$$

where P_H is in kilobars. Here all coefficients are of the same sign. In the same manner in which the arbitrary function $g(V)$ was determined, an arbitrary function $F(\mu)$ was found to fit the equation of state to the form

$$P(\mu,E) = bE + F(\mu) \qquad (10)$$

the function $F(\mu)$ is given by

$$F(\mu) = -8.375 + 768.28\mu + 545.5\mu^2 + 523.97\mu^3 \qquad (11)$$

Another form in which Eq. (10) can be used is

$$P(\mu,E) = P_H(\mu)\left[1 - \frac{b\mu}{2\rho}\right] + b(E - E_o) \qquad (12)$$

where $P_H(\mu)$ is given by Eq. (9) and $b = 5.15\ gm/cm^3$. Comparing Eqs. (10) and (12) it is seen that $F(\mu)$ is simply a fit to

$$F(\mu) = P_H(\mu)\left[1 - \frac{b\mu}{2c}\right] - bE_o \qquad (13)$$

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13 ABSTRACT (Distribution Limitation Statement No. 2)

The pressure-volume energy (P-V-E) equation of state of aluminum and Teflon has been investigated. The P-V-E equation of state of a material is needed to solve nonreactive flow problems using computer codes such as PUFF. Explosively induced shock waves have been used to generate Hugoniot curves for solid and porous specimens of aluminum and Teflon. For aluminum it is found that the following P-V-E equation of state can reproduce the experimental data quite nicely:

$$P = bE + g(V)$$

b is a constant and g is an arbitrary function of V. This corresponds to *Γ Γ/V = constant, where Γ is Gruneisen's ratio. Because of the spread of the Teflon data in the P-V plane, it was not possible to obtain a P-V-E fit. However, the data imply that Gruneisen's ratio varies from about 0.7 to 1.4 at high pressures. Gas gun experiments using manganin wire pressure recordings were performed. Sound speeds deduced from these records imply that Teflon becomes anomalously stiff under shock.

*gamma

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Gruneisen parameter						
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